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Abstract: The present contribution discusses the thermal behavior of a passive solar wall composed of a glazing facing the outside, a channel filled with highly insulating and translucent silica aerogel, and glass bricks filled with an eutectic phase change material (PCM), facing the inside. First, the experimental building with the tested wall, south-oriented, is described. Second, the experimental results on four different weather conditions are detailed. Thanks to a numerical model, the wall behavior is simulated for the French climatic zones of Nice (Mediterranean climate), La Rochelle (oceanic climate), Embrun (inland mountain climate) and Nancy (cold continental climate). Results show that the wall is translucent and may save 27% to 83 % on the building energy bill for heating, depending on the building location. The wall performs best on cold sunny climates, where the phase change can occur all year. The air temperature inside the building is always 1 to 9°C above the external temperature. Overheating may occur in summer for Mediterranean and oceanic climates when the PCM stays in liquid state. This may be prevented by the use of shading.

Keywords: silica aerogel, phase change materials, passive solar design, greenhouse effect

1. Introduction

The share of the building sector in primary energy consumption is about 43% in France [1] and 40% worldwide [2]. To reduce their energy needs for heating, buildings are becoming more and more insulated. Insulation thicknesses over 30cm or use of very low U-value insulation materials are becoming a standard. At the same time, the use of passive solar architectures is strongly encouraged. Among these, Trombe walls [3] and wallboard-integrated phase change materials (PCMs) have been extensively investigated by the industrial and academic community [4-9; 10-15].

Trombe walls consist of an external glazing separated from an internal high thermal capacitance wall by an air channel which may be ventilated or not. Thanks to the greenhouse effect, the channel is heated and the heat is transferred to the house through the wall and/or by the natural convection of the air in the channel. PCMs are materials which undergo a solid to liquid change of phase when they absorb heat. At night, the stored heat is released to the building as the PCM becomes solid again. Several commercial wallboards with embedded PCMs are already available [16-19].

Though useful to reduce the energy bill, high-thickness insulation, Trombe walls and wallboard-integrated PCMs induce a loss of visual daylight comfort because they are opaque. The present contribution investigates an innovative passive solar wall providing at the same time very high insulation, heat storage and day lighting. The wall is composed of a glazing facing the outside, an air gap filled with high insulation silica aerogels materials, and glass bricks filled with an eutectic PCM on the inside. The whole wall is translucent.

The next section of this paper details the solar wall structure and the full-scale experimental building. Section 3 presents the thermal behavior of the wall and the associated room under four typical weather conditions of Sophia Antipolis, France. Based on a numerical model of the wall, section 4 discusses its performance when used in four French climatic zones, Nice (Mediterranean climate), La Rochelle (oceanic climate), Embrun (inland mountain climate) and Nancy (cold continental climate). Finally, the wall’s overall behavior, performances and limitations are discussed in section 5.

2. Presentation of the solar wall structure and of the experimental building

The solar wall structure and the test building are shown on figure 1. The facility is situated in Sophia Antipolis, South France. The building is a lightweight structure composed of two twin rooms on the south side of the building, and one acquisition room on the north. The walls of both twin rooms have the same structure, except for their south facing wall. One twin room is called the reference room since it serves as reference for the validation of technologies deployed in the test room. In the reference room, the south facing wall is made of concrete, glass wool and plaster. In the test room, the south facing wall is the tested PCM-aerogel solar wall. The thermo-physical properties of the solar wall and the reference wall are given on tables 1 and 2 respectively. The surface areas of the solar wall and the reference wall are 4.41m² and 7.15m² respectively.

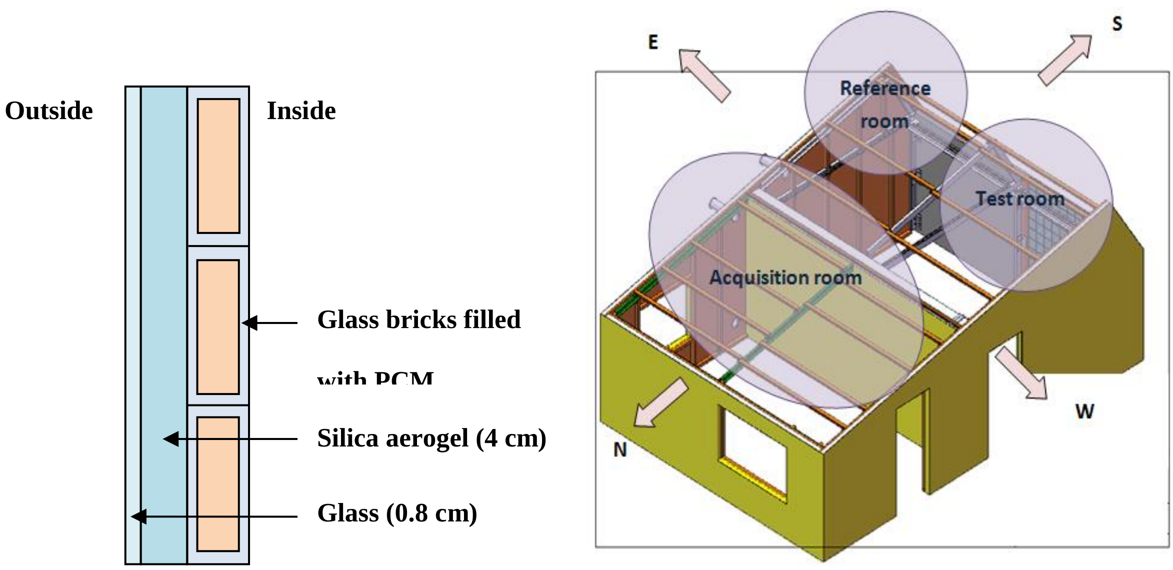


Fig. 1: Layout of the PCM-aerogels solar wall and schematic presentation of the test building

Phase change material (eutectic)	Phase change temperature	21.3 °C
	Phase change enthalpy	152 kJ.kg^{-1}
	Heat capacity (solid)	1670 J.kg^{-1}.K^{-1}
	Heat capacity (liquid)	2090 J.kg^{-1}.K^{-1}
	Density (solid)	884 kg.m^{-3} (at 35 °C)
	Density (liquid)	960 kg.m^{-3} (at 13 °C)
	Thermal conductivity (solid/liquid)	0.182 W.m^{-1}.K^{-1}
Silica aerogel	Particle size	0.5 to 4.0 mm
	Pore diameter	20 nm
	Porosity	> 90 %
	Surface area	600 to 800 m².g^{-1}
	Density	90 to 100 kg.m^{-3}
	Thermal conductivity	0.018 W.m^{-1}.K^{-1} (at 25 °C)

Table 1. Thermo-physical properties of the PCM-aerogel passive solar wall

Materials (from outside to inside)	Width (m)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Specific heat ($J.kg^{-1}.K^{-1}$)	Density ($kg.m^{-3}$)
Concrete	0.25	2.1	800	2400
Glass wool	0.16	0.041	840	12
Plaster	0.013	0.32	800	790

Table 2. Thermo-physical properties of the reference wall

The connecting wall between the reference room and the test room is made of 5cm glass wool insulation with 1.3cm plaster layer on each side. Both rooms are connected to the acquisition room by a wall composed of plaster (1.3cm), glass wool (16cm), concrete (25cm) and phenol-formalin foam (7.7cm). The East and West walls of the test building are composed of plaster (1.3cm), glass wool (16cm), timber panel (1.9cm) and expanded polystyrene (8cm). The floor is made of tiles (1.5cm), concrete (15cm) and expanded polystyrene (8cm). The ceiling is made of plaster (1.3cm), glass wool (16cm), and timber panels (1.2cm), phenol-formalin foam (6cm), another layer of timber panels (1.2cm), rafters and tiling. The walls have been described from inside to outside. The external coating is pale brown and the inner walls are white.

The solar wall temperature is monitored by the use of PT100 sensors of precision ±0.4°C. The sensors are situated on the wall inner and outer surfaces, inside the silica aerogel bed and within the PCM filled glass bricks. Outside the building, both vertical and horizontal solar radiation is measured by two pyranometers of accuracy ±15% of the read value. The temperature and relative humidity of the outdoor and indoor air are recorded using all-in-one Prosensor HYGR0018 THAC sensors of precision ±0.4°C for temperature and ±3% of the read value for humidity. Last, the outdoor and indoor daylight intensity is measured by luxmeters of precision ±5% of the read value.

Figure 2 shows an external view of the PCM-aerogel wall. The six valves on top of the wall are used to fill in the gap behind the glazing with silica aerogel material. PT100 sensors attached to the wall can be seen on the figure.

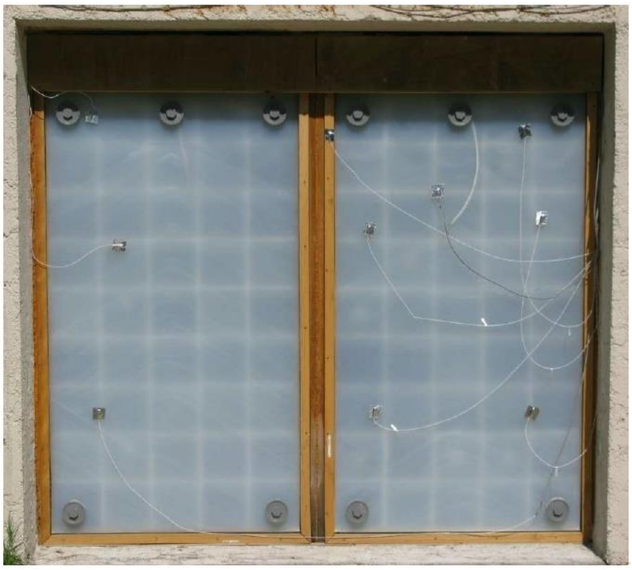


Fig. 2. External view of the PCM-aerogel passive solar wall

3. Experimental results

During the experiment, the test building was left in free floating conditions without internal loads. Figure 3 shows the recorded heat flux entering the test room and the reference room through the south wall under four weather conditions: three consecutive sunny days in December (figure 3.1), three consecutive winter days with low solar radiation in January (figure 3.2), three consecutive sunny days during mid-season in March (figure 3.3) and three hot summer days in August (figure 3.4).

On cold sunny days in December, outdoor air temperature varied from 7 to 18°C and solar radiation on the south oriented vertical plan was high. Under these conditions, the solar wall provided a far greater amount of heat flux to the room than the reference wall. A constant heat release by the solar wall of about 50W/m² occurred from 4pm to 5am, this time corresponding to the crystallization of the PCM. After its crystallization, some sensible heat was still released to the building as the PCM were cooling down. The cycling of the PCM can be observed on figure 3.1. The silica aerogel insulation prevented direct long wave radiation heat transfers to and from the building and the indoor air temperature in the test room varied from 17 to 20°C (see figure 4.1).

During winter days with low solar radiation on the south oriented vertical plane, the PCM would remain in solid state. The outdoor temperature varied from 4 to 11°C. The solar wall did not bring any substantial improvement compared to the reference wall, except for its higher thermal resistance. Some heat loss of about -2W/m² could be observed at night.

On sunny March days, outdoor air temperature varied from 8 to 25°C. The PCM would achieve neither complete fusion nor complete crystallization, even at night. Nevertheless, the amount of heat released to the room, around 50W/m², was significantly higher than that of the reference wall (about 2W/m²) and would remain constant for a longer period of time than during cold sunny days.

During hot summer days, the outdoor air temperature varied from 23 to 40°C. The PCM remained in liquid state in spite of the lower solar radiation on the vertical plane. This is due to the internal and external air temperature almost always remaining higher than the crystallization temperature. The air temperature in the test room always remained between 35 and 40°C while the air temperature in the reference room varied from 32 to 33°C.

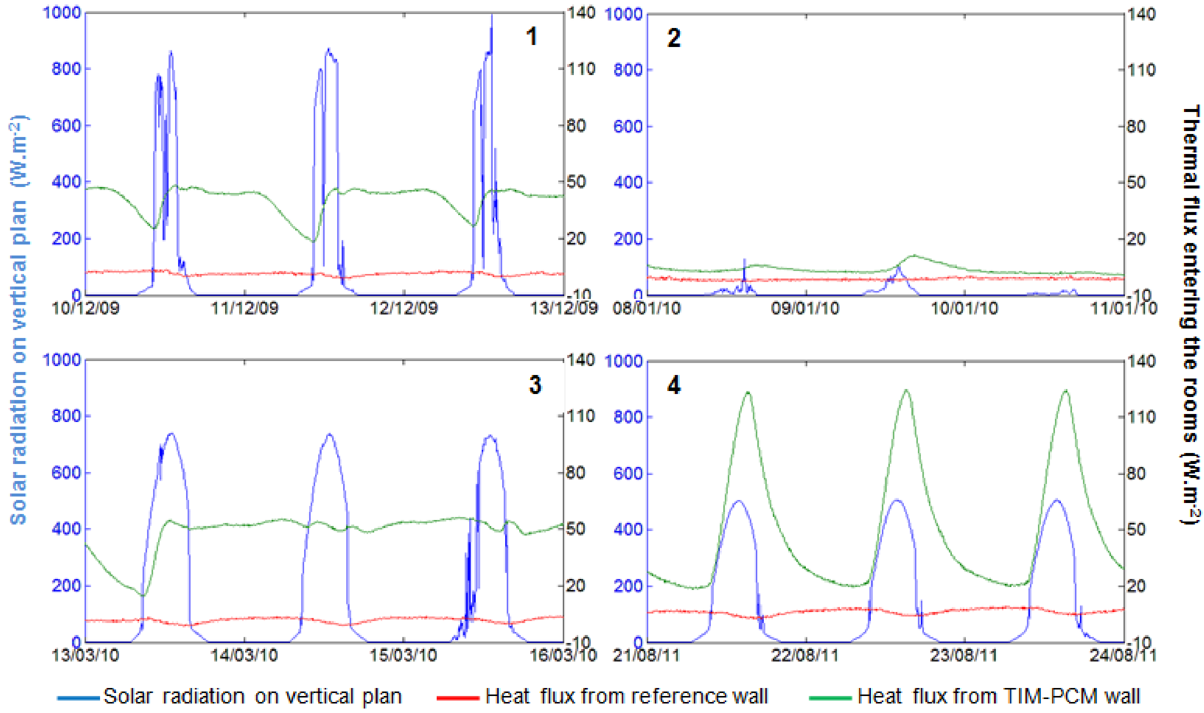


Fig. 3. Solar radiation and heat gains through the reference wall and the PCM-aerogel wall for four weather conditions in Sophia Antipolis, France

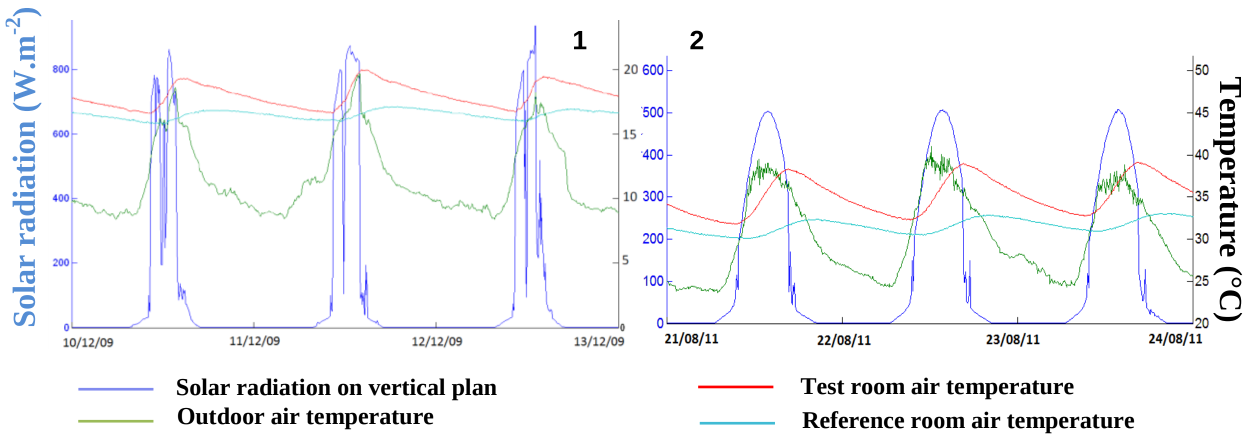


Fig. 4. Solar radiation and air temperatures for three days in December and August

Let us define the time lag and decrement factor of the tested walls as follows:

$$Time\ lag = t(T_{out\_max}) - t(T_{in\_max}) \qquad (1)$$

$$Decrement\ factor = \frac{T_{in\_\max} - T_{in\_\min}}{T_{out\_\max} - T_{out\_\min}} \qquad (2)$$

where t stands for time and T_{out_max}, T_{out_min}, T_{in_max} and T_{in_min} respectively stand for maximum and minimum outdoor temperature and the maximum and minimum indoor temperature. The time lag represents the time shift between the outdoor and indoor peaks of temperature while the decrement factor shows the ability of the wall to reduce for the indoor air, the variation amplitude of the outdoor air temperature. As shown on figure 3, the time lag of the PCM-aerogel wall was about 3 hours in winter and 4 hours in summer while the time lag of the reference wall was 4 hours in winter and 8 hours in summer. The decrement factor for the PCM-aerogel wall was about 0.3 in winter and summer while it was about 0.1 for the reference wall. Lower performances in term of time lag and decrement factor for the PCM-aerogel wall are due to its translucent characteristic: Thermal energy from short wave radiation is directly transmitted to the walls inside the test room and the air is heated up while it is not the case in the reference room.

Figure 4.1 shows that the PCM-aerogel wall performs better than the reference wall during cold sunny days: at night a minimum temperature difference of 5°C and a maximum temperature difference of 9°C could be observed between the test room air and the outdoor air (respectively 4 and 7.5°C for the reference room). In summer time, this characteristic of the solar wall becomes a drawback as the test room was subjected to overheating (see figure 4.2).

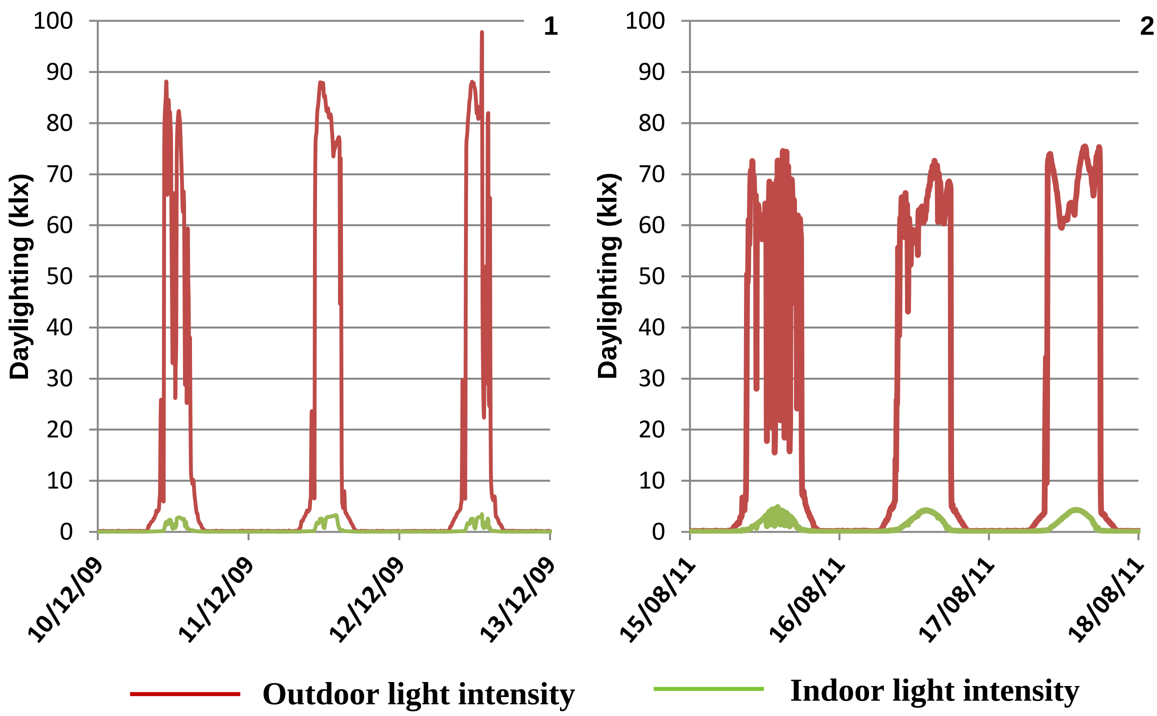


Fig. 5: Measurements of the daylighting within the test room for three days in December and August

Figure 5 shows the measured light transmission through the PCM-aerogel wall when the PCM is in solid state (figure 4.1) and when it is in liquid state (figure 4.2). With the PCM in solid state, the wall could transfer a maximum of 3klx of daylight. Actually, most of the light was transferred through the translucent edges of glass bricks since the PCM was mostly opaque. With the PCM in liquid state the wall transferred up to 5klx to the room, this amount corresponding to a daylight factor of 6.7%. The daylight would be transferred to the room through the PCM and the brick edges. Figure 6 shows the wall appearance from inside the test room in both situations. The light provided by the wall was deemed acceptable for conference rooms and offices.

Fig. 6. Daylight provided by the PCM-aerogel wall with the PCM in solid state (left) and liquid state (right). The picture is taken from inside the test room.

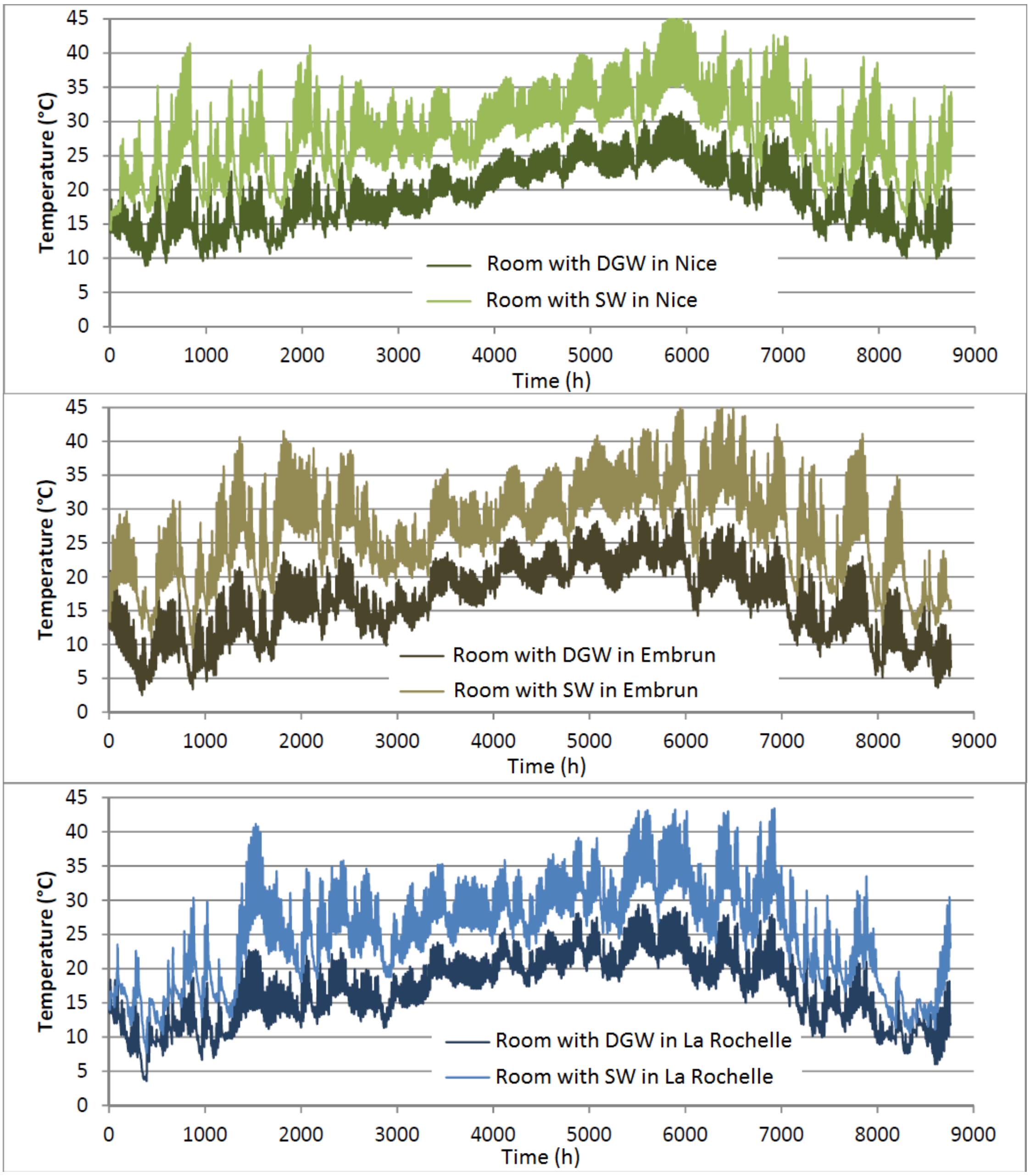
4. Study of the wall performance under four climatic zones

The performance of the PCM aerogel wall was simulated for the French climatic zones of Nice (Mediterranean climate), La Rochelle (oceanic climate), Embrun (inland mountain climate) and Nancy (cold continental climate) by the use of a numerical model.

The numerical model resolves the heat transfer equations though the wall using one-dimensional finite differences. The wall is considered opaque to long wave radiation meaning that long wave heat transfers are considered only for the first node (facing the external environment) and last node (facing the room)on the wall discretization. Inside the wall, only conduction and short wave radiation are simulated. The phase change in the glass bricks is simulated using the enthalpy method [20]. This numerical model of the solar wall, implemented in Matlab programming environment, was connected to the TRNSYS building simulation software to simulate the whole test building under the four above mentioned climatic zones. More details on the numerical model can be found in [21].

The hourly ambient temperature in the test room for the climatic zone of Nice, Embrun, La Rochelle and Nancy is shown on figure 7. The air temperature due to the PCM-aerogel wall was compared to the air temperature obtained by replacing the solar wall (SW) by the reference wall equipped with a 1.5m² double-glazing window (DGW). It was found that the PCM-aerogel wall can provide higher indoor air temperature than the wall with DGW for all climates. The increase in air temperature is less for the climate of Nancy because of its lower solar radiation on the south facing vertical plane and of its cold climate. The PCM-aerogel wall also causes more overheating in shoulder and summer seasons, especially in the warmer climates of Nice and Embrun (see figure 8). These observations are consistent with the reported behavior of most solar walls. The overheating phenomenon is probably aggravated by the absence of ventilation and shading in the test building.

By replacing the free floating condition by an imposed indoor temperature of 19°C during the cold period, the numerical simulation also showed that the PCM-aerogel can provide 83.9% of the heating load in Nice, 70% in Embrun, 49.1% in La Rochelle, and 27.6% in Nancy. This numbers can be readily explained by the fact that the climate is warmer in Nice. Therefore, buildings in Nice have a lower energy demand for heating than in Nancy and this demand can be almost entirely met by the solar wall alone.



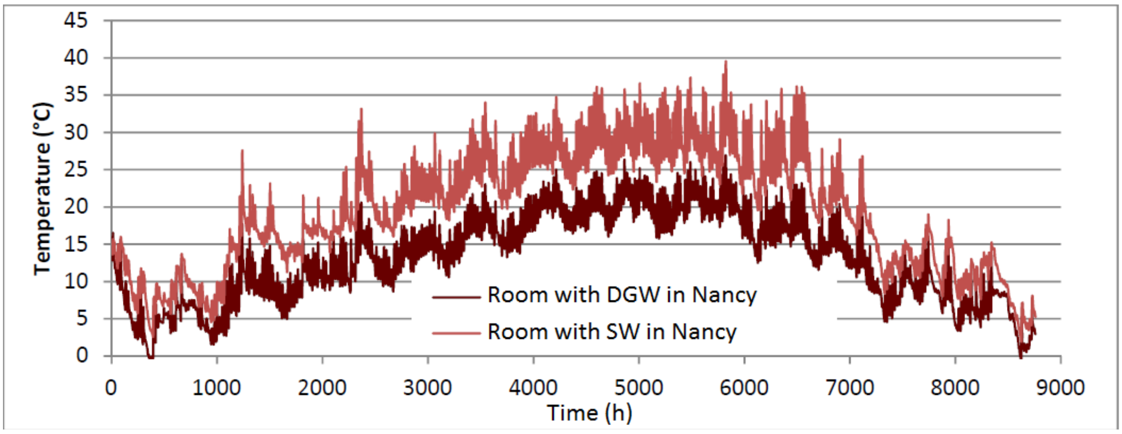
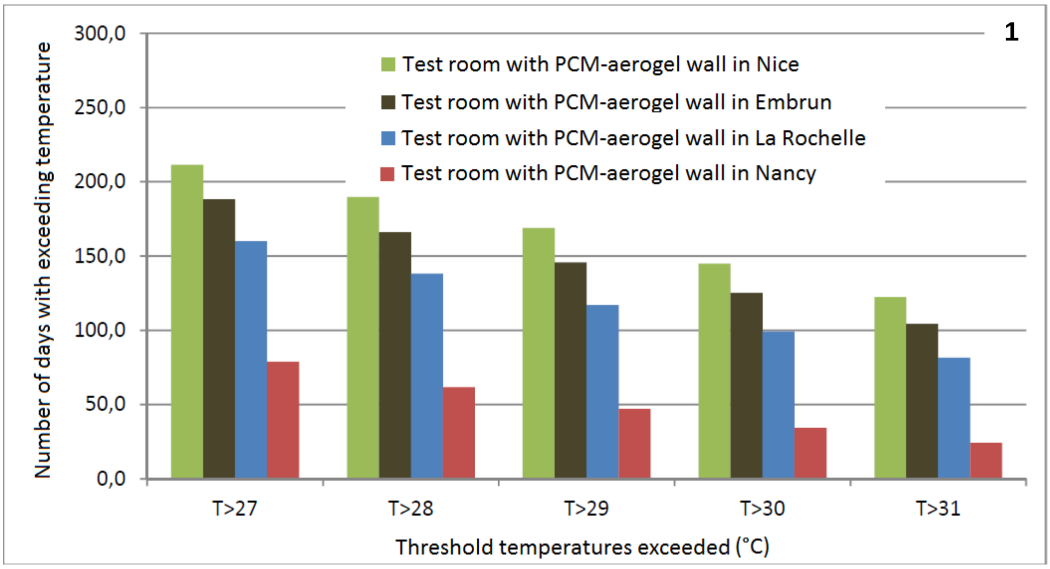


Fig. 7. Simulated hourly ambient temperature in the test room for the climatic zone of Nice, Embrun, La Rochelle and Nancy with the PCM aerogel wall (SW) and an opaque wall with a 1.5m² double glazed window (DGW).



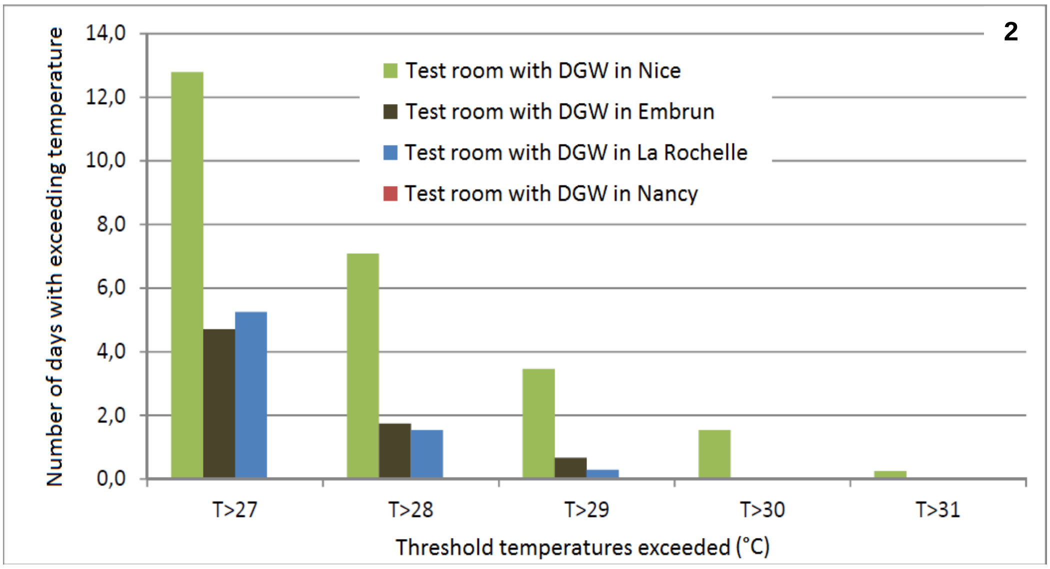


Fig. 8. Number of days with the test room temperature exceeding a threshold in Nice, Embrun, La Rochelle and Nancy. (1) Test room with solar wall. (2) Test room with 1.5m² double glazing window.

5. Conclusion

The present contribution detailed the thermal behavior of an innovative passive solar wall composed of a glazing facing the outdoor environment, a gap filled with highly insulating silica aerogels materials, and glass bricks filled with an eutectic PCM facing the inside. By the combination of two new generation materials for buildings, namely PCMs and silica aerogels, the wall can combines several features that are not found in conventional solar walls: it provides at the same time heat storage, insulation, and daylight comfort to the building.

The wall was tested on a full scale experimental building in Sophia Antipolis, France. Compared to a high capacitance concrete wall, experimental results showed that the PCM-aerogel wall increased the ambient air temperature inside the building by 1 to 5°C, depending on the time of the year. Its time lag was found to be 3 hours in winter and 5 hours in summer, while its decrement factor had a constant value of 0.3. The wall provided enough daylight visual comfort for conference rooms and offices with a daylight factor of 6.7% when the PCM in liquid state. It was noticed that even in the absence of direct horizontal solar radiation on the wall, heat losses through the wall remained low, thanks to its high thermal insulation.

The performance of the PCM aerogel wall was simulated for the French climatic zones of Nice (Mediterranean climate), La Rochelle (oceanic climate), Embrun (inland mountain climate) and Nancy (cold continental climate) by the use of a numerical model of the test building. It was shown that the wall performs better in cold sunny climates with high temperature differences between days and nights, since this situation allows the phase change to occur. The numerical simulation also showed that the wall can cover 83.9% of the heating needs in Nice, 70% in Embrun, 49.1% in La Rochelle, and 27.6% in Nancy.

A limitation of the PCM-aerogel wall was observed in summer and shoulder seasons in warm climates. In this case, the PCM may remain in liquid state, leading to overheating of the building. This situation may be prevented by the use of shading as soon as the PCM is completely liquid or when the indoor air temperature reaches a predefined comfort value. The PCM-wall may contribute to the cooling of indoor air during warm periods provided the crystallization of the PCM is performed at night. This could be achieved by the use of passive or active cooling strategies such as night ventilation.

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